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The effect of proactive adaptation on green investment

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Abstract

Climate change is one of the greatest challenges facing our planet in the foreseeable future and despite the urgency of the situation global GHG emissions are still increasing. In this context, and since future climate changes appear now unavoidable to some extent, adaptation measures have recently gained a new political momentum as an important component of climate policies. Contrary to mitigation options, adaptation measures do not reduce emission levels but reduce their impacts. To assess the relationship and effects on the global economy of both mitigation and adaptation, we use in this paper an integrated assessment model (IAM) that includes both proactive adaptation strategies and access to "green" investments (clean technologies) for mitigation. We find that the relationship between adaptation and mitigation is complex and largely dependent on their respective attributes, with weakly effective adaptation acting as a late complement to mitigation efforts. As its effectiveness increases, adaptation becomes more and more a substitute for mitigation. Sensitivity analysis on the potential magnitude of damages also indicates that scientific efforts to better describe GHG impacts will have immediate and important consequences on the sequence of mitigation and adaptation strategies.

Keywords: Adaptation, Climate change, Mitigation, Clean technology, Integrated assessment
JEL: Q54, Q55

1. Introduction

Climate change is one of the greatest challenges facing our planet in the foreseeable future. It is expected, according to the Intergovernmental Panel on Climate Change (IPCC, 2007), to impact

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ecosystems and the environmental services they provide (in terms of food and water in particular) but also human societies (affecting human health and regional economies, for instance). Besides, the IPCC argues that human activities, through the greenhouse gases (GHG) they release in the atmosphere, are responsible for most of the observed increase in global average temperatures up to now. Furthermore, the IPCC estimates that, in the absence of ambitious climate policies to reduce anthropogenic GHG emissions, global warming will continue at an accelerated pace.

Despite the urgency of the situation, global GHG emissions are still increasing, in particular because there is not yet an overall agreement to curb world emissions. In this context, and since future climate changes appear now unavoidable to some extent, adaptation measures have recently gained a new political momentum as an important component of climate polices. Contrary to mitigation options, adaptation measures do not reduce emission levels, but provide strategies to deal effectively with climate change effects by reducing their impacts (Tol, 2005; Adger et al., 2007; Klein et al., 2007b). Adaptation strategies cover a large array of sectors and options, from new agricultural crops, modified urban planning (dikes, sewerage systems), medical preventions against pandemic to controlled migrations of population and activity changes. Depending on the degree of anticipation (and requirement for it), adaptation measures can be preventive or reactive: vaccination campaigns can be made mandatory without any materialized threat (as precautionary principle) or could be implemented only in reaction to pandemic urgency, for instance.

Compared to mitigation strategies, adaptation measures have several strengths. On the one hand, in the case of "reactive" adaptation, benefits should be rapidly achieved. This short lag between costs and benefits should reduce adaptation exposure to uncertainty and discounting preferences. This should also be beneficial for populations already vulnerable to certain impacts of climate change (Parry et al., 2009). On the other hand, "preventive" adaptation should provide long-lasting effects that may incur delays before being effective, a feature similar to mitigation. Moreover, adaptation measures in effect privatize policies against climate changes by largely limiting the benefits of adaptation to those having invested in it. Adaptation avoids the free-riding problem traditionally associated with mitigation[3] and does not require concerted and simultaneous actions, fostering the advancement of regional or local projects. As pointed by Olson (1965), "*only a separate and 'selective' incentive will stimulate a rational individual in a latent group to act in a group-oriented way*" and to that goal, adaptation is effective. However, adaptation measures are not exempt from drawbacks. Since they have at best very limited impact on the causes of climate change, they may encourage unsustainable emission trajectories. They are therefore highly vulnerable to catastrophic climate thresholds. Moreover, as pointed out by de Bruin and Dellink (2011b), uncertainty about the exact impacts of climate change may prevent optimal levels of adaptation. Finally, it seems highly questionable that adaptation measures by themselves will be sufficient to fully protect populations from all the damages of climate change, and thus some levels of mitigation should also be implemented.

Both international institutions and governments have recognized these strengths and have now started to conceive and finance portfolios of adaptation projects. For instance, the World Bank has initiated a US$500 million Pilot Program for Climate Resilience and prepared in 2009 a new study to assess adaptation costs, areas and applicability in developing countries (Margulis and Narain, 2009). Under the United Nations Framework Convention on Climate Change (UNFCCC), a new adaptation fund has also been launched, financed with 2% of the shares of proceeds coming from the issuances of certified emission reduction units (CERs) under the clean development mechanism (CDM). During the recent Copenhagen conference (COP15), it was also decided to create the Copenhagen Green Climate Fund (CGCF), with a first budget of US$30 billion in the 2010-2012 period to invest in mitigation and adaptation projects. This fund should eventually reach US$100 billion by 2020 (United Nations, 2009). In addition to those dedicated projects, adaptation strategies are now more and more blended into more traditional development projects and official development assistances (ODA) (Klein et al., 2007a). They are also

[3] A country say may hesitate to pay for emission reductions that will also impact favorably those who did not participate in any mitigating efforts, thus unbalancing its competitiveness (Olson, 1965; Baumol and Oates, 1988).

pushed forward in developed countries albeit without the kind of targeted recognition used for developing countries.

Considering the simultaneous promotion of adaptation strategies and the relative weaknesses of mitigation policies so far, the question of their respective role should be assessed, both for policy and investment purposes. It could be that adaptation strategies become inexpensive alternatives to mitigation approaches, at least as long as no clear international agreement forces the world's economies to transition into an more efficient economy (in terms of GHG emissions). If this is the case, what would be the impact on the transition timing towards such an economy? More importantly, what could be the long run effects, both in terms of GHG concentrations, overall costs and damages and growth trajectories?

To answer these questions, one may use an integrated assessment, an interdisciplinary approach that uses information from different fields of knowledge, in particular socio-economy and climatology. Integrated assessment models (IAMs) are tools for conducting an integrated assessment, as they typically combine key elements of the economic and biophysical systems, elements that underlie the anthropogenic global climate change phenomenon. Examples of IAMs are DICE (Nordhaus, 1994, 2008), MERGE (Manne et al., 1995; Manne and Richels, 2005), RICE (Nordhaus and Yang, 1996) and TIAM (Loulou and Labriet, 2008; Loulou, 2008).

Research incorporating adaptation measures into integrated assessment models has been rare until recently, despite the importance of these models for current policy decisions. Hope et al. (1993) (updated in Hope, 2006) were the first to integrate adaptation as a policy variable in an IAM, the PAGE model. Bosello (2008) uses a FEEM-RICE model with both adaptation and mitigation options. de Bruin et al. (2009b) have proposed to include adaptation as an explicit strategy in the DICE model (AD-DICE). In follow-up studies, de Bruin et al. (2009a) expand this methodology to the RICE model (AD-RICE), Felgenhauer and de Bruin (2009) introduce uncertainty in the climate outcome, Hof et al. (2009) test for the effectiveness of the 2% levy proposed to finance the UNFCCC adaptation fund in a combined AD-RICE/FAIR model, de Bruin and Dellink (2011b) explore the effects of restrictions (barriers) to adaptation with AD-DICE (AD-DICE08), and de Bruin (2011a) advances further the modeling of adaptation in AD-DICE (AD-DICE09). Finally, Bosello et al. (2010) have proposed to consider adaptation within the WITCH model (AD-WITCH). Note also that Agrawala et al. (2010) present a comprehensive "*inter-model comparison of results*" from AD-DICE, AD-RICE and AD-WITCH.

We use in this paper the deterministic version of a simple integrated assessment model (Bahn et al., 2008, 2010, thereafter referred to as BaHaMa) enriched to consider explicitly adaptation options.[4] BaHaMa is in the spirit of the DICE model but distinguishes between two types of economy: the "carbon economy" (our present economy) where a high level of fossil fuels is necessary to obtain output and a so-called "carbon-free" or "clean economy" (an hydrogen economy, for instance) that relies much less on fossil fuels to produce the economic good. In terms of energy sector representation, our model stands therefore somehow between DICE and WITCH, as the latter model includes a detailed bottom-up representation of the energy sector distinguishing in particular among 7 different energy technologies. Likewise, in terms of adaptation modeling, our model stands somehow between the AD-DICE08 model (de Bruin and Dellink, 2011b) and the models AD-DICE09 (de Bruin, 2011a) and AD-WITCH (Bosello et al., 2010). In the former model, adaptation efforts are considered as costs ("*flow*") only. In our approach, we consider adaptation efforts as investments ("*stock*"). As such, we emphasize the proactive component of adaptation in lieu of its reactive element (see Lecocq and Shalizi, 2007). This choice is motivated by Agrawala et al. (2010, p. 11) that claim that "*... adaptation will consist predominantly of investments in adaptation stock...*".[5] Note however that AD-DICE09 and AD-WITCH consider

[4]Given the rather sophisticated treatment of uncertainty (through a stochastic control approach) in the original BaHaMa model and the complexity of the numerical approach involved to solve this model, we have chosen as a first step and for simplicity to implement adaptation only in a deterministic version of BaHaMa. A more interesting and meaningful approach would be to include adaptation in the original BaHaMa model. We leave this for a future research.

[5]Agrawala et al. (2010, p. 11) add also that "*This does not necessarily imply that fewer reactive or "flow" adaptation actions will be undertaken. Rather, investments in adaptation infrastructure ... might tend to be more expensive, and would therefore tend to dominate the adaptation budget.*" In that respect, our approach should be

both reactive and proactive adaptation. Despite these simplifications in the modeling of the energy sector (compared to WITCH) and in the modeling of adaptation (compared to AD-DICE09 and AD-WITCH), our objective is to contribute with a new IAM to an adaptation literature that so far relies only on a very limited number of (peer reviewed) models. Besides, compared to the different versions of AD-DICE, our approach provides a better representation of the energy sector. We can therefore assess the timing of adoption of clean technologies in the presence of adaptation strategies and evaluate the sensitivity of their interactions to specific parameters. This element could be of importance in the current debate about the required incentives to foster adequate "green" R&D investments. Moreover, our model, while being close in certain aspects to the DICE model for comparison purposes, remains largely autonomous in its calibration procedure, allowing us to test a variety of parameter's specifications.

The paper is structured as follows. Section 2 details our IAM with explicit adaptation options, thereafter referred to as Ada-BaHaMa. The section covers also some of the economic rationales behind the modeling choices. Sections 3 and 4 give the model's results and sensitivity analyses on adaptation effectiveness and climate sensitivity. Section 5 provide a comparison of our results with the ones of the existing literature. Finally we conclude in Section 6 and propose some further improvements that provide additional directions for research.

2. BaHaMa with explicit adaptation

2.1. Model description

An overview of Ada-BaHaMa is given in Fig.1.

We next describe the different component of the original BaHaMa model and its new adaptation feature.

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viewed as a first modeling exercise only. We leave a more sophisticated modeling of adaptation for future research.

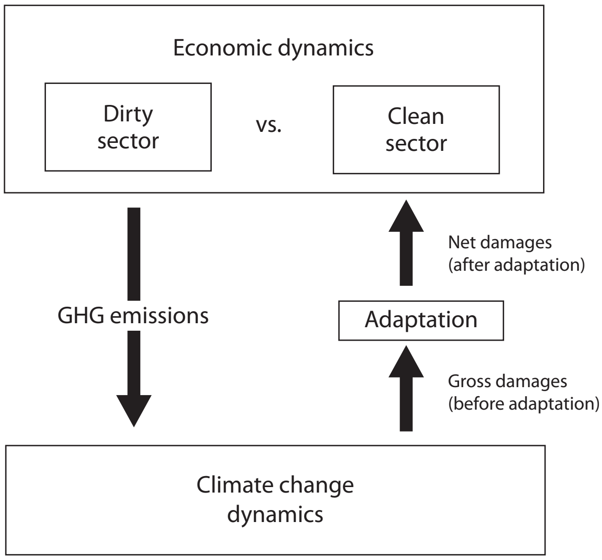

Figure 1: Schematic overview of Ada-BaMaMa.

2.1.1. Production dynamics

Production (Y) occurs in the two types of economy (the carbon economy, referred to by an index 1, and the clean economy, referred to by an index 2) according to an extended Cobb-Douglas production function in three inputs, capital (K), labor (L) and energy (measured through GHG emission level E):

$$\begin{aligned} Y(t) = & A_1(t)K_1(t)^{\alpha_1}(\phi_1(t)E_1(t))^{\theta_1(t)}L_1(t)^{1-\alpha_1-\theta_1(t)} \\ & + A_2(t)K_2(t)^{\alpha_2}(\phi_2(t)E_2(t))^{\theta_2(t)}L_2(t)^{1-\alpha_2-\theta_2(t)}, \end{aligned} \tag{1}$$

where for each economy i ($i = 1,2$): A_i is the total factor productivity, α_i the elasticity of output with respect to capital K_i, ϕ_i the energy efficiency and θ_i the elasticity of output with respect to emissions. Notice that capital stock in each economy evolves according to the choice of investment (I_i) and a depreciation rate δ_{K_i} through a standard relationship:

$$K_i(t+1) = I_i(t) + (1-\delta_{K_i})K_i(t) \quad i = 1,2. \tag{2}$$

Besides, total labor (L) is divided between labor allocated to the carbon economy (L_1) and labor allocated to the carbon-free economy (L_2):

$$L(t) = L_1(t) + L_2(t). \tag{3}$$

2.1.2. Climate change dynamics

Stocks of GHGs are computed using the following dynamic equations from the DICE model (Nordhaus, 2008), that distinguish between three reservoirs, an atmospheric reservoir (M_{AT}), a quickly mixing reservoir in the upper oceans and the biosphere (M_{UP}), and a slowly mixing deep-ocean reservoir (M_{LO}) which acts as a long-term sink:

$$M_{AT}(t+1) = (E_1(t)+E_2(t)) + \psi_{11}M_{AT}(t) + \psi_{21}M_{UP}(t) \tag{4}$$

$$M_{UP}(t+1) = \psi_{12}M_{AT}(t) + \psi_{22}M_{UP}(t) + \psi_{32}M_{LO}(t) \tag{5}$$

$$M_{LO}(t+1) = \psi_{23}M_{UP}(t) + \psi_{33}M_{LO}(t) \tag{6}$$

where $\psi_{i,j}$ are calibration parameters. Relationship between accumulation of GHGs and temperature deviation is also from DICE and is given by the following equations:

$$F(t) = \eta log_2\left(\frac{M_{AT}(t)}{M_{AT}(1750)}\right) + F_{EX}(t) \tag{7}$$

$$T_{AT}(t+1) = T_{AT}(t) + \xi_1\left[F(t+1) - \xi_2 T_{AT}(t) - \xi_3\left(T_{AT}(t) - T_{LO}(t)\right)\right] \tag{8}$$

$$T_{LO}(t+1) = T_{LO}(t) + \xi_4\left(T_{AT}(t) - T_{LO}(t)\right) \tag{9}$$

where F is the total atmospheric radiative forcing, F_{EX} an exogenous radiative forcing term, T_{AT} the earth's mean surface temperature, T_{LO} the average temperature of the deep oceans, and ξ_i and η calibration parameters for an assumed climate sensitivity of 3 °C that corresponds to the best estimate[6] given by the IPCC (Meehl et al., 2007). Accumulation of GHGs increases the earth radiative forcing, warming the atmosphere and then gradually the oceans. This allows for the existence of inertia between GHG concentration and climate change.

2.1.3. Damage and adaptation frameworks

To model climate change damages and their economic impacts, we follow an approach used in the MERGE model (Manne and Richels, 2005). We compute in particular an economic loss factor (ELF) due to climate changes at time t, which is adapted to take into account the effects of adaptation $\mathrm{AD}(t)$ as follows:

$$\mathrm{ELF}(t) = 1 - \mathrm{AD}(t) \left(\frac{T_{AT}(t) - T_d}{cat_T - T_d} \right)^2, \tag{10}$$

where T_d is the temperature deviation (from pre-industrial level) at which damages start to occur and cat_T is the climate sensitivity dependent “catastrophic” temperature level at which the entire production would be wiped out. For the illustrative purposes of this paper and to have a comparable basis with the current literature on IAM with adaptation, T_d and cat_T are calibrated in order to replicate the damage intensity of DICE; see Section 2.2. Notice further that this loss factor applies on production levels, see Section 2.1.4, such that damages are computed as: $\mathrm{AD}(t)Y(t)\left(\frac{T_{AT}(t)-T_d}{cat_T-T_d}\right)^2$.

In our model, adaptation reduces the damaging effects of GHG concentration and, to simplify, has neither impact on the total factor productivity (no innovation breakthrough is coming from

[6] In Section 4, we test our model for different values of climate sensitivity, using the ‘likely’ range of 2–4.5 °C given by the IPCC.

adaptation investment) nor direct correlation with GHG emissions (as in the often cited air conditioned example). Contrary to the recent efforts by de Bruin and Dellink (2011b) that model adaptation as a cost (flow), but in a fashion similar to Bosello (2008), we consider adaptation as an investment (stock). To use the words of Lecocq and Shalizi (2007), we thus favour the proactive type of adaptation over the reactive one. This modeling choice is motivated by the expectation that, for a large part, adaptation projects will be directed towards infrastructure and medium-to-long-term economic transformations. This view is supported by Agrawala et al. (2010) that conclude their comparison of results from AD-DICE, AD-RICE and AD-WITCH stating that, p. 11, "... *adaptation will consist predominantly of investments in adaptation stock...*".[7] Moreover, using proactive instead of reactive adaptation gives us greater flexibility over the nature of adaptation policies. By controlling for capital depreciation rate in the model, we can test for proactive effectiveness: if adaptation investments are in line with realized impacts, depreciations should be slow. On the contrary, inadequate strategies or incapacity to predict future damages will force to reinvest frequently, imposing a high deprecation rate on the adaptation capital. At the margin, with an annual depreciation of 100%, the adaption investment corresponds to a cost.

The adaptation dynamics is as follows:

$$\mathrm{AD}(t) = 1 - \alpha_{\mathrm{AD}} \frac{K_3(t)}{K_{3\max}(t)} \tag{11}$$

with α_{AD} representing the maximal adaptation effectiveness, $K_3(t)$ the amount of adaptation capital in period t and $K_{3\max}(t)$ the maximal amount of adaptation capital[8] to be invested in each period to ensure the optimal effectiveness of adaptation strategies.

[7]Note that AD-DICE09 (de Bruin, 2011a) and AD-WITCH (Bosello et al., 2010) consider both reactive and proactive adaptation. Indeed, if one should rely mostly on proactive adaptation when the effects of climate change are still relatively limited, reactive adaptation may become important when damages increase; see for instance Agrawala et al. (2010). Reactive adaptation shall be introduced in Ada-BaHaMa as a component of our future research.

[8]In other words, we impose at all time periods t that $K_3(t) \leq K_{3\max}(t)$.

In our framework, adaptation costs should increase whenever temperature (and therefore damages) broadens. To take this into account, we model $K_{3\max}(t)$ as an increasing function of temperature level:

$$K_{3\max}(t) = \beta_{\mathrm{AD}} \left(\frac{T_{AT}(t)}{T_d} \right)^{\gamma_{\mathrm{AD}}}, \tag{12}$$

where β_{AD} and γ_{AD} are calibration parameters. The behavior of this function is determined by the calibration process. Nonetheless, we force the calibration to be bounded such that $\beta_{\mathrm{AD}} \geq 0$ and $\gamma_{\mathrm{AD}} \geq 1$. Hence, getting the full offsetting potential of adaptation will require more and more investment if mitigation is not also considered jointly.

2.1.4. Welfare maximization

A social planner is assumed to maximize social welfare given by the integral over the model horizon (T) of a discounted utility from per capita consumption $c(t) = C(t)/L(t)$. Pure time preference discount rate is noted ρ and the welfare criterion is then given by:

$$W = \int_0^T e^{-\rho t} L(t) \log[c(t)]\, dt. \tag{13}$$

Consumption comes from an optimized share of production, the remaining being used to invest in the production capital (dirty and/or clean), in the adaptation capital and to pay for energy costs. The presence of damages (defined by the ELF factor) reduces the available production such that:

$$\mathrm{ELF}(t)Y(t) = C(t) + I_1(t) + I_2(t) + I_3(t) + p_{E_1}(t)\phi_1(t)E_1(t) + p_{E_2}(t)\phi_2(t)E_2(t), \tag{14}$$

where I_3 is the investment in the adaptation capital and p_{E_i} are energy prices. Note also that adaptation stock evolves according to a relation similar to Eq. (2):

$$K_3(t+1) = I_3(t) + (1 - \delta_{K_3})K_3(t), \tag{15}$$

where δ_{K_3} is a depreciation rate.

2.2. Model calibration

The different modules of Ada-BaHaMa (adaptation, economy and climate) are basically calibrated on DICE (version 2007[9], thereafter referred to as DICE2007) and on the original AD-DICE model (de Bruin et al., 2009b).

We start our calibration procedure by the adaptation component which is new the feature in the Ada-BaHaMa model. First, we calibrate ex-ante parameters defining the maximal amount of efficient adaptation capital ($K_{3\max}$). We use for this a recent report that the World Bank (Margulis and Narain, 2009) issued on the cost of adaptation in developing countries for the period 2005-2055: to fully offset[10] climate change impacts in developing countries, US$ 100 billion should be spent each year until 2055. Despite representing only a small share of the global economy, these adaptation costs, when adjusted for our model, still correspond to high values compared to the AD-DICE estimates. They are also conservatively close to the estimates obtained in Bosello et al. (2010). Second, the maximal adaptation effectiveness (parameter α_{AD}) is set to 0.33 (at most 33% of damages are avoided)[11] following results reported with AD-DICE. Third, to reproduce the magnitude of climate change damages estimated by DICE and AD-DICE, we use values of GHG concentration, temperature, gross damage and production from these models in order to calibrate parameters of our damage function (ELF). Consequently, our damage estimates follow rather closely those of AD-DICE as displayed in Fig. 2.

The other modules of Ada-BaHaMa (economy and climate) are again basically calibrated on

[9] See: http://www.econ.yale.edu/ nordhaus/DICE2007.htm.

[10] This view that climate change damages can be fully offset is obviously optimistic and certainly questionable. Note however that such an "optimistic" view is somehow shared by Mendelsohn (2000) that estimates that some climate damages could be reduced by up to 80%, and thus almost fully offset. Besides, in our calibration approach, (Margulis and Narain, 2009) is only used as a benchmark.

[11] However and considering its importance in the determination of the optimal mix of strategies, we conduct in Section 4 sensitivity analyses for different–lower and higher–values of α_{AD}.

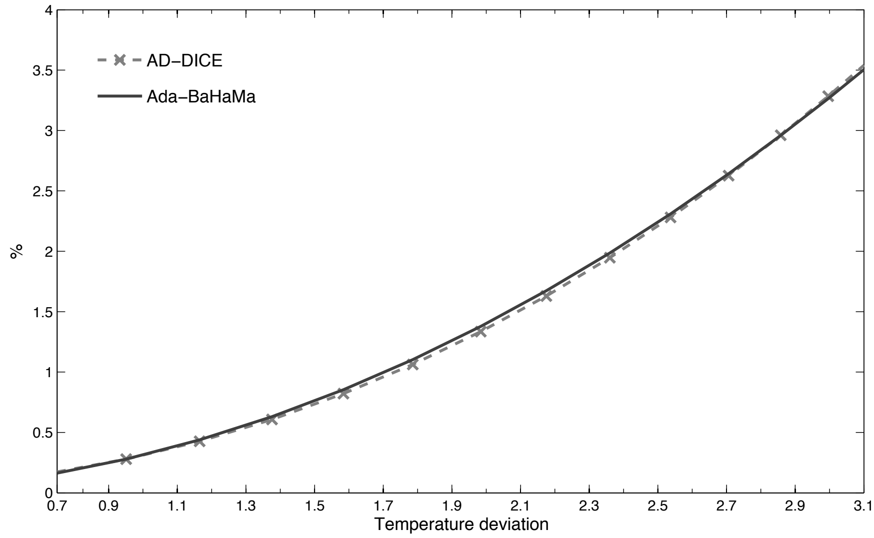

Figure 2: Damage levels (in percentage of production) for different temperature increases in Ada-BaHaMa and AD-DICE (in °C).

DICE2007. In particular, parameters in Eqs. (1), (2) and (4) to (9) are mostly from DICE2007. Moreover, we calibrate our (counterfactual) baseline, in which only the current dirty economy is producing, to match as closely as possible production, concentration and temperature trajectories of the DICE2007 baseline (see Figs. 3 and 4, where our baseline is labelled "Ada-BaHaMa Dirty economy only" and DICE2007 baseline "DICE2007 No Controls"). However, compared to the dirty economy, production in the clean economy has better energy efficiency but higher energy costs in the short term. To calibrate our clean economy, we rely on a progressive deployment path of "advanced" clean energy technologies, following results obtained with the MERGE model (Manne and Richels, 2005) when imposing as constraints the temperature levels reached in Ada-BaHaMa. The clean technologies we focus on correspond on the one hand to advanced "high-cost" electricity generation systems (relying on biomass, nuclear, solar and/or wind) whose capacity is not limited, and on the other hand to an unlimited carbon-free supply of non-electric energy (such as technologies producing hydrogen using carbon-free processes). Since Ada-BaHaMa does not distinguish among different clean technologies, we summarize in our model the two most distinctive elements of the clean economy development path according to MERGE: when clean technologies are first significantly deployed (around 2045, following MERGE results) and when they become the main energy production mean (around 2075, following MERGE results).[12] Calibrating our clean economy on MERGE, we are thus able to benefit from the MERGE detailed portfolio of energy technologies (MERGE distinguishes between 13 electricity generation technologies and 7 sources of non-electric energy supply) and of its estimate of their respective contribution to energy supply. Interestingly, at the end of our calibration procedure, the resulting overall production in Ada-BaHaMa happens to reproduce the economic output of DICE2007, at least until the first quarter of the 22nd century; cf. Fig. 3 (comparing the trajectory labelled "Ada-BaHaMa" with the one labelled "DICE2007").

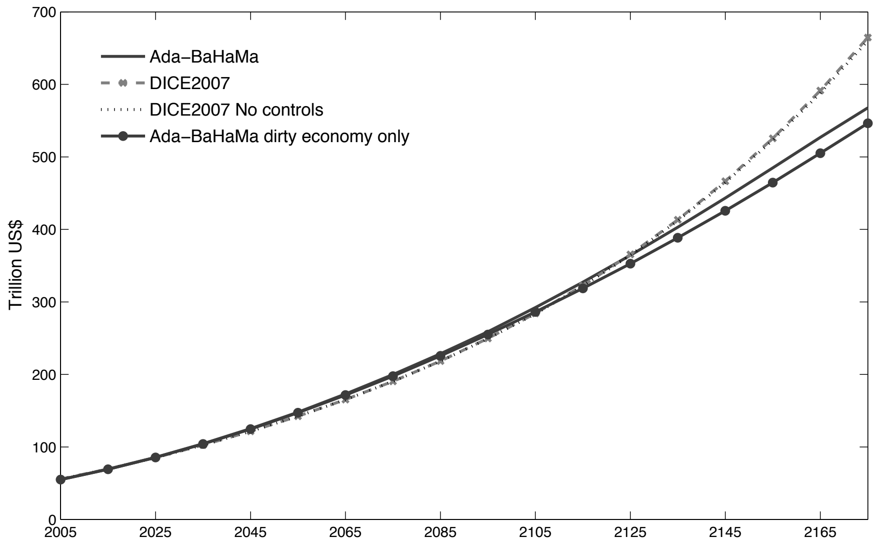

Figure 3: Economic production paths in Ada-BaHaMa and DICE2007.

Note however that, compared to DICE2007, the modeling of two types of economies implies an optimal trajectory, conditioned by a transition to the clean economy after 2055 to reduce

[12]See the trajectory labelled "Mitigation only" in Fig. 6, page 17. We have indeed calibrated the clean economy for a scenario where only mitigation strategies are possible; see also Section 3 below.

climate change damages, that involves much less GHG emissions and thus lower temperature increase over the long run; cf. Fig. 4 (comparing the trajectory labelled "Ada-BaHaMa" with the one labelled "DICE2007").

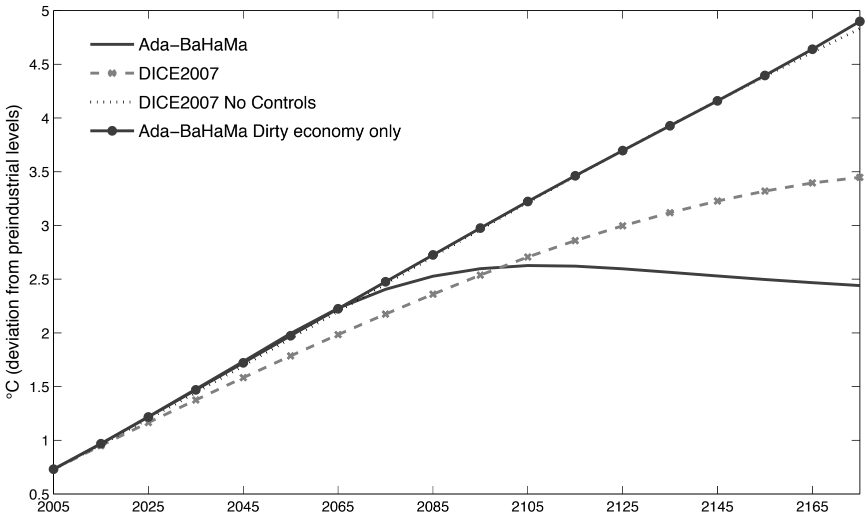

Figure 4: Temperature deviation paths in Ada-BaHaMa and DICE2007 (in $^\circ$C).

3. Results

In this section, we report on four different scenarios: a counterfactual baseline without any adaptation or mitigation (investments in the clean technology) efforts, an adaptation-only scenario where the clean technology is not available, a mitigation-only scenario where adaptation is not possible and finally a combined scenario with both mitigation and adaptation efforts. More precisely, we first detail impacts of these scenarios on dirty and clean production capital stocks as well as on adaptation capital stocks. We then look at effects on climate change and the corresponding damages. Finally, we detail the overall effects on economic output.

3.1. Capital accumulation paths

When comparing our scenarios, two important components stand out in the strategies deployed to address climate change: first, the existence and timing of a transition between the dirty and the clean economy (mitigation strategy), see Fig. 5 and 6, and second, the importance awarded to adaptation, especially when the clean technology is not available, see Fig. 7.

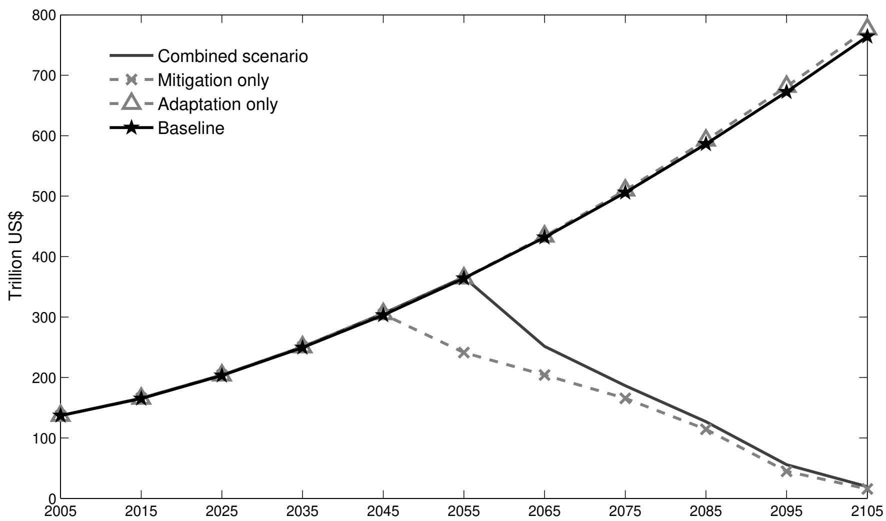

Figure 5: “Dirty” capital K_1 accumulation paths.

When the clean technology is not available (adaptation-only scenario), clean capital does not of course accumulate. In addition, accumulation of dirty capital is slightly higher compared to the baseline scenario, as (net) damages and thus the necessity to limit dirty production are reduced through adaptation. Conversely, when the clean technology is available (mitigation-only and combined scenarios), there is a clear transition between the two economies: dirty capital is rapidly phased out after 2045 or 2055 and almost completely replaced by clean capital by the end of the century. Discrepancies coming from not allowing adaptation (mitigation-only scenario) are noticeable, as a transition from dirty to clean capital is started ten years earlier to prevent harmful damage levels.

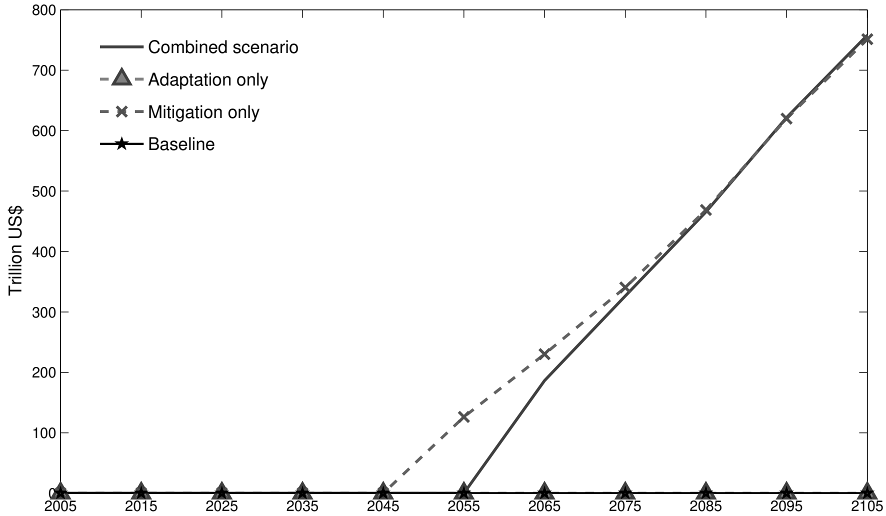

Figure 6: "Clean" capital K_2 accumulation paths.

As far as adaptation capital is concerned, it does not of course accumulate in the mitigation-only scenario (where the adaptation option is not available). Both in the adaptation-only and combined scenarios, adaptation is used after 2045, where the accumulation of adaptation capital (K_3) reaches immediately its maximal level ($K_{3\max}$) and stays at this level afterwards. In this two scenarios, the delay in implementing adaptation measures results from the low-effectiveness of adaptation and signs a trade-off between costs of adaptation and its positive effect on welfare. In Section 4.1, we will test for different values of adaptation effectiveness. Notice also that the maximal level of adaptation capital ($K_{3\max}$) depends on temperature level; cf. Eq. (12). As the latter reaches lower levels in the combined scenario (see Fig. 9, page 20) due to the transition to the clean economy, the required amount of capital for a maximal effectiveness of adaptation is significantly reduced in this scenario (compared to the adaptation-only scenario).

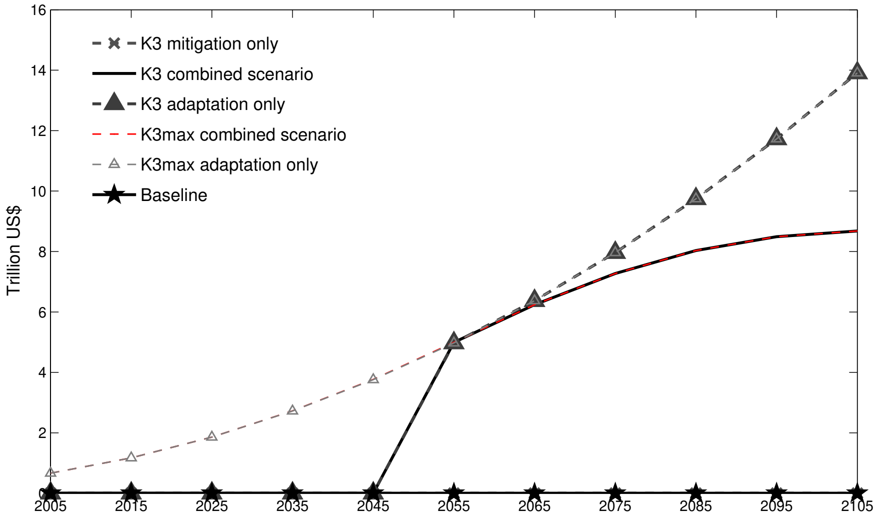

Figure 7: Adaptation capital K_3 accumulation paths and maximal amount of adaptation capital ($K_{3\max}$).

3.2. GHG concentration, temperature and net damages

Greenhouse gas concentration in the atmosphere, given in Fig. 8, follows the mitigation efforts detailed in the previous Section 3.1. Thanks to the rapid adoption of clean technologies (after 2045) in the mitigation-only scenario and the corresponding transition toward a cleaner economy, concentrations in the mitigation-only scenario peaks in 2075 and temperature increase (given in Fig. 9, page 20) stabilizes by the end of the century around 2.5 °C. For the combined scenario, the offsetting effect of adaptation, postponing the transition to "green investment" by about 10 years, has for consequence a higher concentration peak (reached in 2075) and temperature increase stabilizes by the end of the century slightly above 2.6 °C. Conversely in the adaptation-only scenario, the lowest mitigation effort (with dirty production being slightly higher than the "business-as-usual" baseline), concentration keeps always increasing as well as temperature that reaches around 3.3 °C by the end of the century.

Temperature increase translates directly into gross damages; cf. Eq. (10). Hence as reported in Fig. 10, page 21, net damages in the mitigation-only scenario (that correspond to gross

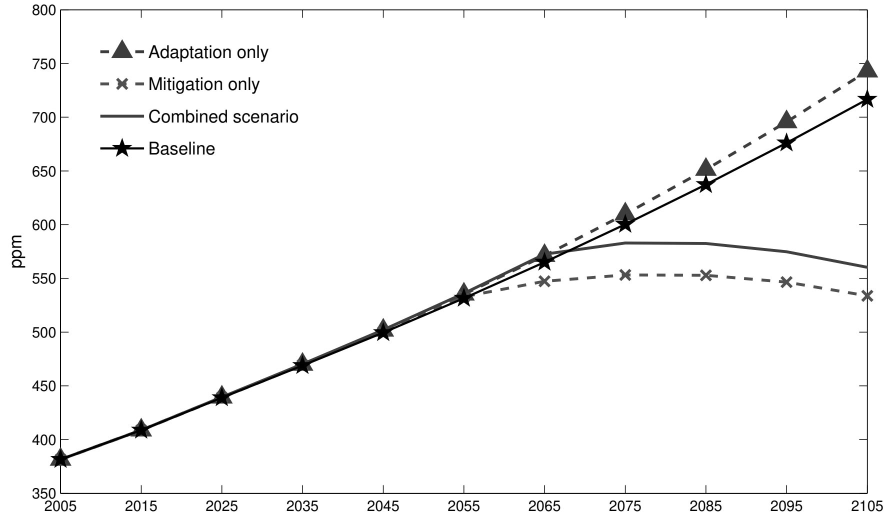

Figure 8: GHG concentration paths.

damages in the absence of adaptation) peak at the end of the century (2105) before gradually decreasing. Gross damages may however be "reduced" through adaptation. In the adaptation-only scenario, net damages are initially reduced (by 2055, compared to the mitigation-only scenario) when adaptation measures start to be implemented. But as they immediately reach their full potential (33% of gross damages avoided) they cannot afterwards compensate for the continuous increase in temperature and thus in damages. When both adaptation measures and adoption of clean technologies are enacted in the combined scenario, it is interesting to note that exposure to damages is the lowest of all scenarios.

3.3. Economic output paths

Fig. 11, page 21, reports on GDP losses due to climate change damages, with the combined scenario being used as a comparative level. As expected, reducing the choice of policy options to address climate changes yields an overall decrease in economic output compared to the combined scenario. This is in particular the case in the adaptation-only scenario over the long

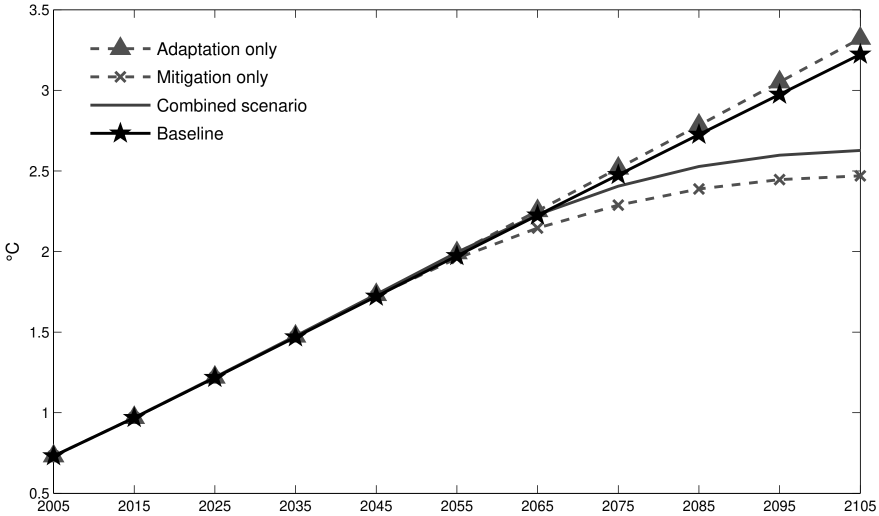

Figure 9: Temperature deviation paths from preindustrial levels (in °C).

term, where the inability to prevent significant temperature increase (thus significant net damages) yields increasing GDP losses. The decrease in economic output is also significant in the mitigation-only strategy. Note that the absence of massive adaptation investments (to the detriment of investments in production capital) in period 2055 allows for a short-lived surplus over the adaptation-only strategy (but below the combined strategy). Besides, GDP losses are again lower at the end of the century (compared to the adaptation-only strategy) as one reaps the benefits of limiting temperature increase. Here, preventing the use of adaptation measures is indeed not very disadvantageous for the economy due to our low setting for adaptation effectiveness (at most only 33% of damages can be avoided).

4. Sensitivity analysis

The influence played by adaptation measures on the timing of adoption of clean technologies is largely dependent upon certain key parameters, like the degree of adaptation effectiveness or the climate sensitivity assumed in the model. In sections 4.1 and 4.2, we test for different levels for

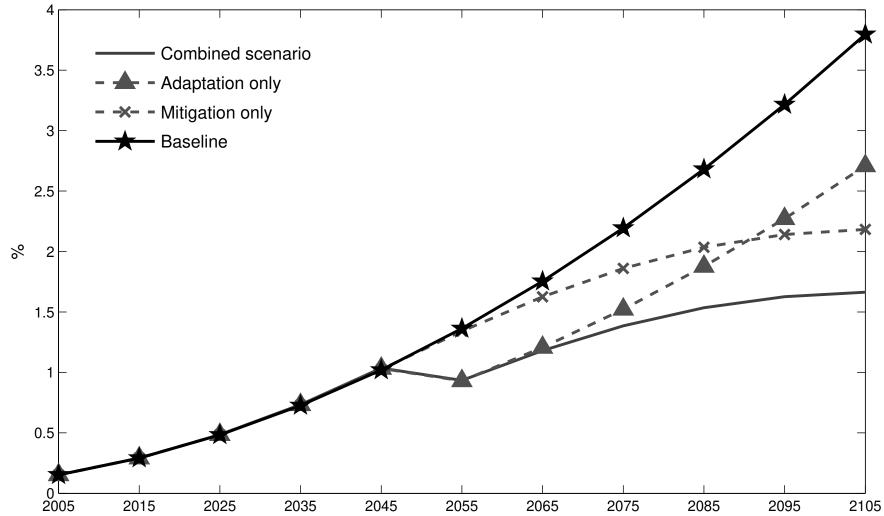

Figure 10: Evolution of net damages.

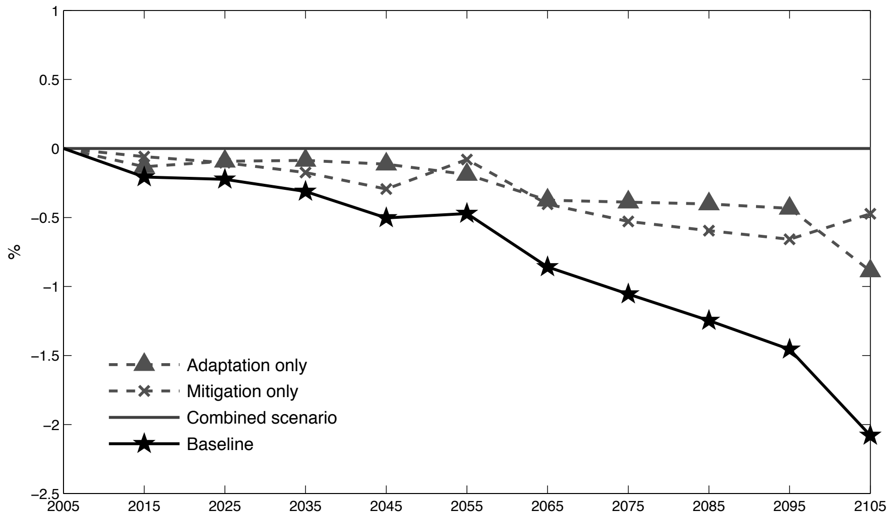

Figure 11: Economic output difference (in %) relative to the combined scenario.

these two key parameters.

4.1. Sensitivity analysis on adaptation effectiveness

According to past and current research on adaptation policies, it seems indisputable that the effectiveness of adaptation measures will be highly influenced by geographical, political and societal idiosyncrasies, as well as by the quality and reliability of preventive efforts which in turns largely depend upon the accuracy of damage predictions. Considering the high level of uncertainty surrounding damage assessments, our basic parameter setting uses a relatively low level of effectiveness for adaptation. As such, it penalizes regions for which adaptation could be both inexpensive and efficient. For instance, Agrawala et al. (2010) reports that costal adaptation could offset up to 95% of costal damages in the case of India. At the end of the spectrum, the World Bank[13] (Margulis and Narain, 2009) reports that adaptation in developing countries could be completely effective and fully offset climate change damages in all sectors. Although likely over-optimistic, an effectiveness level of 100% ($\alpha_{\mathrm{AD}} = 1$) can thus be also envisioned (if only to test the view of Margulis and Narain, 2009).

When increasing the adaptation effectiveness, we observe a strong substitution effect between increasingly efficient adaptation measures and adoption of clean technologies. As reported in Fig. 12 and 13, the adoption of clean technologies is delayed by a few decades (or even postponed after 2105 for $\alpha \geq 0.8$) and its preventive role against climate change damages is replaced by adaptation measures.

Note that a stronger reliance on adaptation has the drawback of pushing temperature to much higher levels; see Fig. 14, page 25. For instance, with a value of 100% for the adaptation effectiveness, temperature increase reaches 3.7 °C by 2105 (compared to around 2.6 °C under our standard setting). By shielding the world's economy from (most of) climate change damages, improvement in adaptation effectiveness favours more polluting practices and delays thus a transition toward a cleaner economy.

[13] which provides our cost estimates for the calibration of the maximal amount of efficient adaptation capital $K_{3\max}$.

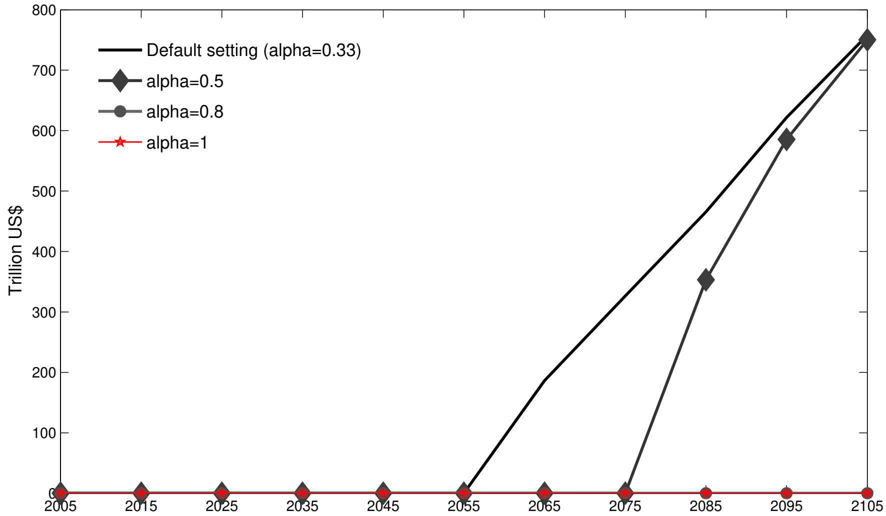

Figure 12: "Clean" capital K_2 accumulation paths for different levels of adaptation effectiveness.

This could however turn out to be a risky policy, especially in presence of uncertainty about climate change effects, which may include "abrupt" changes[14] (see for instance Lenton et al., 2008), which in turn could hinder the capacity to successfully–and continuously–provide efficient adaptive solutions in the future.

4.2. Sensitivity analysis on climate sensitivity

According to the IPCC (2007), the equilibrium impact of doubling atmospheric CO_2 concentration may in average lead to an increase in temperature from pre-industrial levels of about 3 °C, recognizing "*an upper bound of likely range of climate sensitivity of 4.5 °C and lower bound of likely range of climate sensitivity of 2 °C*". To account for this level of uncertainty, which has a direct and immediate impact on damages, we conduct a sensitivity analysis on our combined

[14]Examples of such extreme events include a melting of the West Antarctic ice sheet and a collapse of the Atlantic thermohaline circulation.

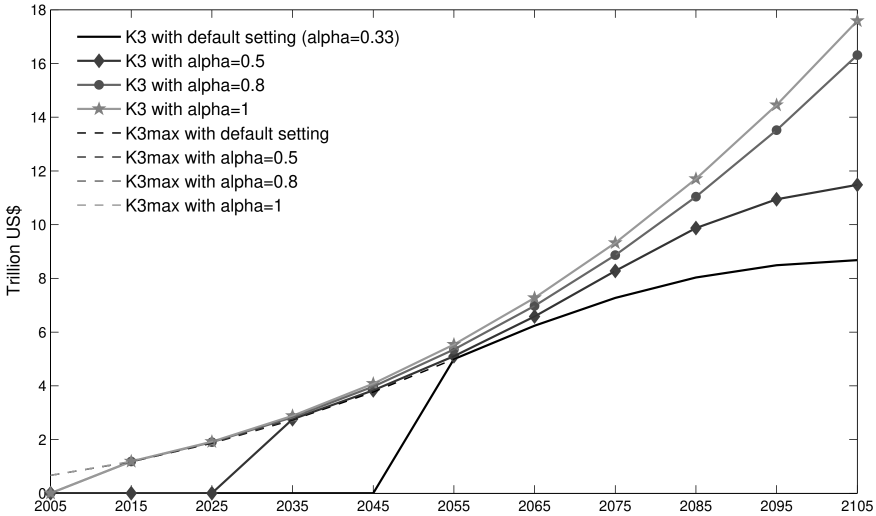

Figure 13: Adaptation capital K_3 accumulation paths and maximal amount of adaptation capital ($K_{3\max}$) for different levels of adaptation effectiveness.

strategy (mitigation and adaptation) for a low (2 °C), medium (3 °C) and "high"[15] (4.5 °C) levels of climate sensitivity. As expected, a low climate sensitivity, yielding lower damages, postpones dramatically "green" investments and the transition towards clean energy. In our simulation, a climate sensitivity of 2 °C delays transition by 40 years. When climate sensitivity is high, we obtain an opposite effect, the transition being speeded up by 20 years; see Fig. 15, page 26, and Fig. 16, page 27.

Adaptation plays here a complementary role, with an identical timing for the three scenarios (starting after 2045) but with different investment levels; see Fig. 17, page 28. Again, higher climate sensitivity yielding larger damages forces a larger investment in adaptation. The convergence towards the end of the century observed in our results for low and medium climate sensitivities can be explained by a similar pattern in temperature increase; see Fig. 18, page 29. A medium climate sensitivity, provoking an earlier transition towards clean production, has the

[15]It must be emphasized that the range of possible values of climate sensitivity may be much wider than those used here; see for instance Stainforth et al. (2005).

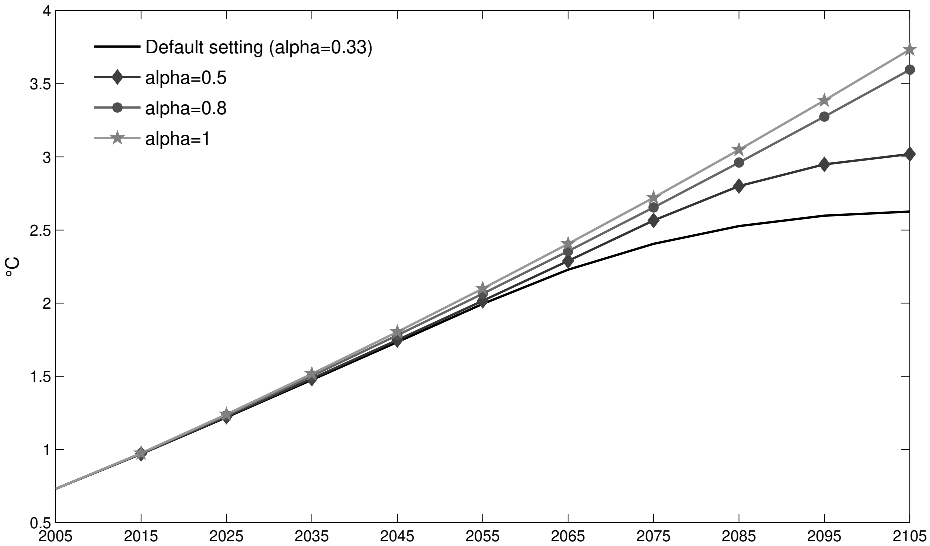

Figure 14: Temperature deviation from preindustrial levels in °C for different levels of adaptation effectiveness.

effect of limiting temperature increase and thus damages by the end of the century. Conversely, for a low climate sensitivity, continuous emissions from "dirty" production until 2095 yield temperature (and thus damages) increase to the point where the two temperature curves converge by the end of the century.

In our sensitivity analysis, it appears clearly that a change of scientific consensus on climate sensitivity will have major effects on the best policy mix to deploy and on its timing. However, because of the relatively high level of uncertainty surrounding this parameter, assuming a "low" climate sensitivity induces the risk that, if this assumption turns wrong, no adaptation policy might be able to offset the potentially irreversible effects due to a large increase in GHG concentration. Mitigation strategy, in the words of Bosello et al. (2010, p. 86), could be "*the starting point. Its characteristics should be determined on the basis of the precautionary principle and independently of adaptation because adaptation cannot avoid irreversibility*".

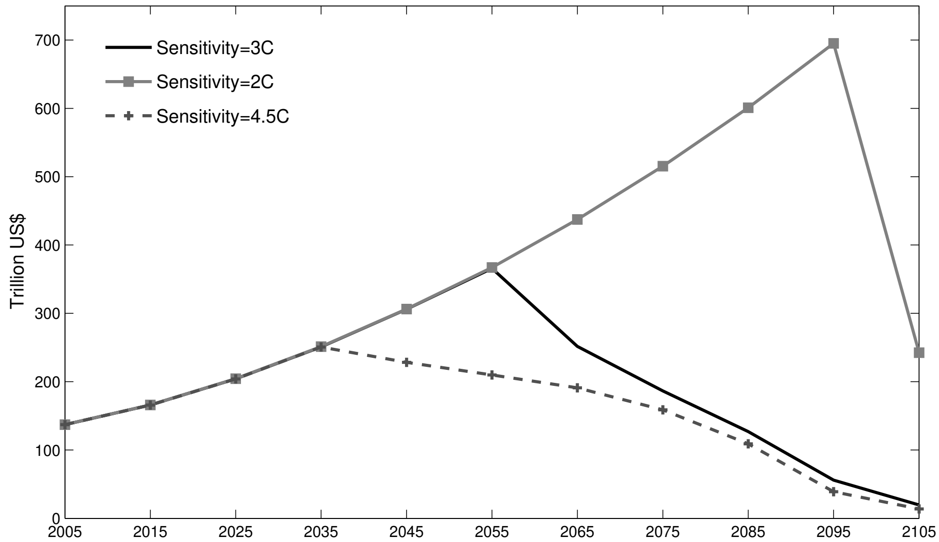

Figure 15: “Dirty” capital K_1 accumulation paths for different climate sensitivity.

5. Comparison to previous studies

Ada-BaHaMa belongs to a limited number of integrated assessment models, such as AD-DICE (de Bruin et al., 2009b; de Bruin and Dellink, 2011b; de Bruin, 2011a), AD-WITCH (Bosello et al., 2010) and FEEM-RICE (Bosello, 2008), that take explicitly into account strategies to adapt to the negative impacts of climate change. The particularity of Ada-BaHaMa is to model both a reactive adaptation strategy through an adaptive capital and a mitigation strategy taking the form of a clean technology. As already stated in Section 1, our model stands somehow between DICE and WITCH in terms of energy sector modeling, and between (the different versions of) AD-DICE and AD-WITCH in terms of adaptation modeling. Having acknowledged these differences in the modeling approaches, we can however compare some insights Ada-BaHaMa provides with the ones obtained with FEEM-RICE, AD-DICE and AD-WITCH.

Bosello (2008) considers in FEEM-RICE proactive adaptation using a dedicated investment variable, therefore modeling the adaptation strategy in a fashion similar to our own. Besides, the efficiency of adaptation depends on the current temperature deviation level, as in our model. It

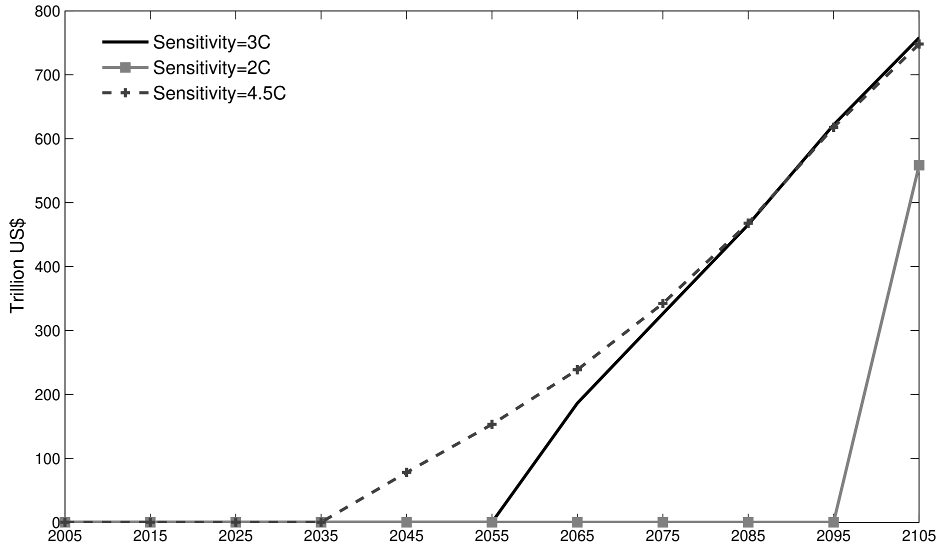

Figure 16: "Clean" capital K_2 accumulation paths for different climate sensitivity.

does not however include a maximum investment in adaptation K_{3max}, therefore expanding the potential of adaptation to offset damages. In our initial setting adaptation efficiency is capped at 33%, while in Bosello (2008, p. 11) adaptation "*starts to be appreciable after 2040 – when damage is reduced the 14% – and booms afterward – when damage is reduced up to the 50%*". As a result, and contrary to Bosello's conclusions, our model finds that adaptation with weak efficiency is triggered *before* mitigation, (except under a high climate sensitivity assumption, where the potential magnitude for damages combined with a weak adaptation efficiency forces to quickly abate GHG emissions).

Similarly to de Bruin et al. (2009b), which incorporates adaptation as a cost option (reactive adaptation) within a DICE structure, we find that in our initial setting mitigation and adaptation act as strategic complement. However, whereas they use a separable model for mitigation and adaptation, we use an interdependent model, in which adaptation costs increase with higher temperature deviation. As a result, whereas they report (p. 74) that "*mitigation decreases the benefits of adaptation*", our results tend to indicate that mitigation could increase adaptation

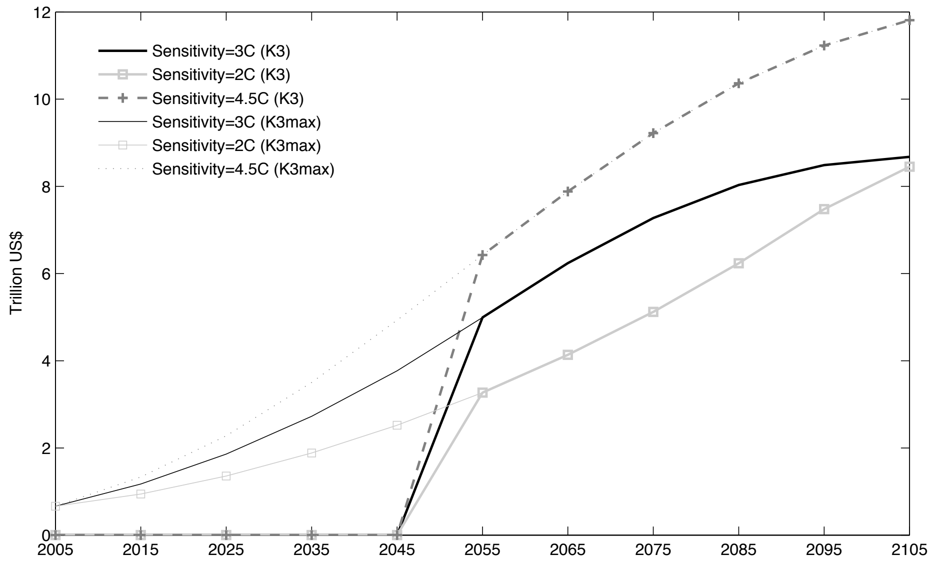

Figure 17: Adaptation capital K_3 accumulation paths and maximal amount of adaptation capital ($K_{3\max}$) for different climate sensitivity.

efficiency by reducing the investments required for its deployment.

Compared to Bosello et al. (2010) which uses the AD-WITCH model, we also find that mitigation and adaptation are strategic complement (at least when adaptation effectiveness is limited). Adaptation "becomes detectable in 2035", a result comparable to our optimal run (in which adaptation starts a decade later, in 2045). However, their model is not constrained by a maximum adaptation investment level and the high discount rate they impose on their initial run decreases the appeal of mitigation. As a result, they find only marginal differences between their adaption-only and mitigation-and-adaptation scenarios, while we observe noticeable differences between the two. As with Bosello (2008), they find that it is optimal to start mitigating before adapting, which is the opposite of our results (again except when assuming a high climate sensitivity).

Finally, in line with de Bruin (2011a) and her AD-DICE09 model, we find that both mitigation and adaptation measures are important in responding to climate change. We also find

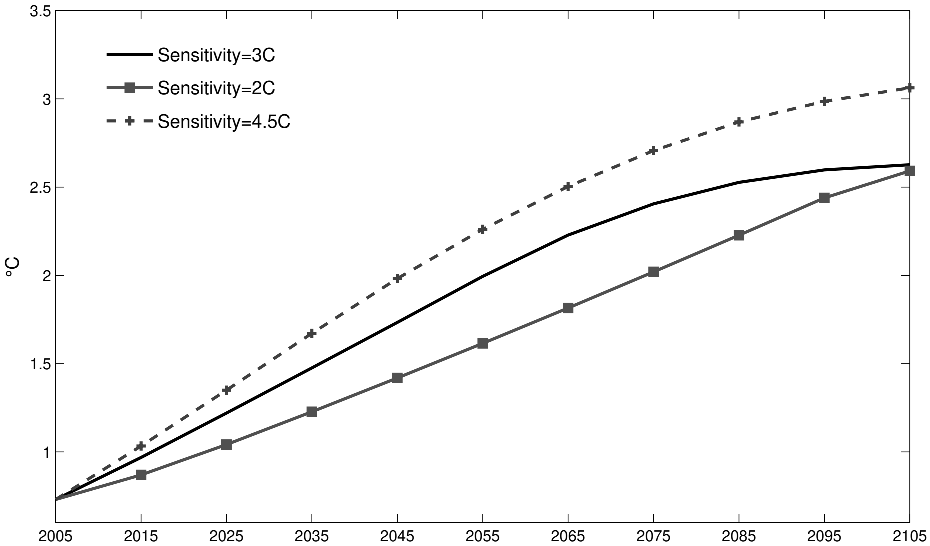

Figure 18: Temperature deviation from preindustrial levels in °C for different climate sensitivity.

that total costs of climate change are the lowest when both mitigation and adaptation are used together. Note that these two insights are also highlighted in Agrawala et al. (2010). However, de Bruin (2011a) finds that there should be a greater emphasis on (proactive) adaptation in earlier decades while adaptation in our model starts comparatively later. This is due to difference in the capital formulation between our two models: adaptation stock in AD-DICE09 is immediately fully effective, whereas in our model adaptation should first reach a required level $K_{3\max}$) to be fully effective. Our approach is more consistent with a situation where adaptation requires full completion to be effective (e.g. dikes building).

6. Conclusion

In this paper, we introduce both adaptation and mitigation strategies as decision variables in an integrated assessment model and assess their respective economic and environmental impacts as well as their influence on each other.

Our model presents several distinctive characteristics in view of the IAM literature on adaptation and mitigation. In terms of adaptation strategy modeling, Ada-BaHAMa stands somehow between the AD-DICE08 model and the models AD-DICE09 and AD-WITCH, focusing on proactive adaptation only (as this form of adaptation is expected to be the dominant one). In terms of mitigation strategy modeling, our model stands somehow between DICE and WITCH, as mitigation is done through a transition towards clean production systems. This sheds light on trade-offs between existing (fossil) technologies and new cleaner (renewable or fossil with carbon capture and sequestration) production systems. Note also that Ada-BaHaMa allows for interaction between adaptation and mitigation. Indeed, we model the required adaptation investment as being dependent on temperature level and thus on the mitigation strategy deployed.

We find that interaction between adaptation and mitigation is complex and largely dependent on their respective attributes. Our results show that adaptation, when weakly effective, is used as a complement to mitigation strategies. Investment in adaptation is done in conjunction with investment in clean production systems and do not hinder the transition from dirty to clean technologies (in our combined scenario). However, resorting to an adaptation-only strategy causes significant temperature increase and thus significant net damages that yield increasing GDP losses. Sensitivity analysis reveals however that this situation changes with increasing adaptation effectiveness. In particular, highly effective adaptation acts as a medium- to long-term substitute to mitigation efforts, that could even prevent long-term investments in clean production systems (in the extreme case of perfectly efficient and certainly unrealistic adaptation measures). Analysis on the climate sensitivity indicates also that the choice of a climate sensitivity parameter is certainly not innocuous on the policy recommendations and represents a crucial element for our mitigation/adaptation model. In our framework, higher climate sensitivity has in particular the effect of accelerating mitigation efforts while increasing adaptation investments. On the opposite end of the sensitivity spectrum, a low sensitivity value hinders significantly the mitigation efforts and reduces adaptation investments.

We view this paper has an essential (first) step for implementing adaptation in the BaHaMa model. But we do envision several other steps to enrich the modeling framework of Ada-BaHaMa, to be carried out in future research. A first improvement will be to consider simultaneously reactive and proactive adaptation strategies to better capture the different adaptation options. Besides, we also acknowledge that the choice of adaptation and mitigation policies has to take into account heterogeneity in regional costs, exposures and achievable benefits. Therefore, a second improvement of our model will be the development of a multi-regional version of Ada-BaHaMa, building on the two-region version of BaHaMa reported in Bahn et al. (2010). A third important improvement will be to introduce uncertainty, for instance on the magnitude of climate change damages, on the adaptation effectiveness or on a technological breakthrough that would provide access to the clean economy. As in Bahn et al. (2008), the resolution of uncertainty could be modeled as a stochastic control problem.

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